# ULTRASOUND GENERATION IN COMPOSITES VIA EMBEDDED OPTICAL FIBERS

Daniel L. Balageas, Nicolas Jaroslavsky, Marc Dupont and François Lepoutre
Office National d'Etudes et de Recherches Aérospatiales
BP 72, 92322 Châtillon cedex, France

Jean-Charles Gonthier and Lionel Bertrand
Ecole Polytechnique de Montreal, Departement de Génie Physique
C. P. 6079, succ. Centre-Ville, Montreal, Quebec, Canada H3C 3A7

## INTRODUCTION

The laser based ultrasound generation is now a well known and established technique used in NDE and material characterization [1]. The use of embedded optical fiber sensors in structures made of composite materials is of great interest for smart structures allowing an integrated health monitoring. The combination of both techniques could lead to an optical fiber based ultrasonic embedded system comprising both ultrasounds sources and detectors.

The laser generation of ultrasounds through embedded optical fibers is only considered here. We present preliminary results of such an ultrasounds generation in a carbon-epoxy material using 100 μm inner core optical fibers guiding pulses of roughly 1 mJ energy and 200 ns duration. The detection of the produced ultrasounds is achieved using a laser probe heterodyne interferometer.

The problem treated in this paper is the research of the types and amplitudes of the ultrasounds generated through a fiber and the knowledge of the input levels which produce destructive effect. These experiments have been used to compare the generation of ultrasounds in the following conditions : fiber outside the composite, fiber embedded in the composite after the process, fiber embedded in the composite during the process.

Moreover, in order to increase the limit value of the destruction threshold, a fourth experiment with colored resins which absorb progressively the laser pulse is presented. Finally, a post-test destructive examination of the sample with embedded fibers will be discussed.

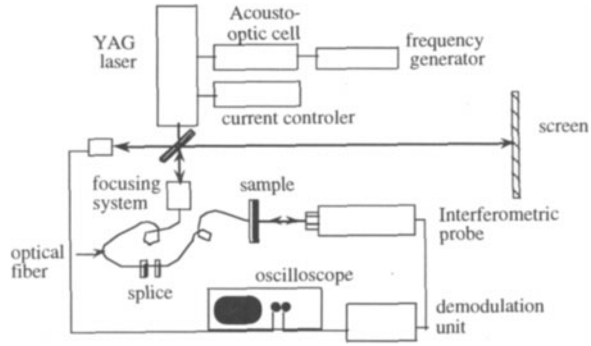


Figure 1. Experimental arrangement.

EXPERIMENTAL PROCEDURE

The experimental set-up is shown in figure 1. The source is a continuous pumped Nd : YAG laser operating at 1.064 μm, Q-switched by an acousto-optic modulator which delivers repetitive pulses. Figure 2 gives the output characteristics of this source. A small part of the beam, splitted by a plate, is directed to a fast photodiode to trigger the detection, the main part is introduced into an optical fiber by means of an aspheric lens (f=11 mm, numerical aperture N.A. = 0.25). The sample is holded in a XYZ translator stage. The detection is performed by using a Mach-Zehnder heterodyne interferometer (BMI interferometric probe). The probe is sensitive to the out-of-plane displacements. Its large bandwidth extends from 20 kHz to 30 MHz with a sensitivity better than $10^{-6}$ nm/$\sqrt{Hz}$ on mirror-like surfaces and about $5.10^{-5}$ nm/$\sqrt{Hz}$ on scattering surfaces. The optical fibers used here are 100 μm -dia. core, 110 μm -dia. cladding and 125 μm -dia. polyimide coating and are prepared with SMA connectors. The N.A. of the fibers is 0.19. The beam is focused on the fiber and the reflected beam passes through the splitter and is visualized on a screen, which is helpful for a good coupling and to avoid damage at the input face of the fiber. The output of the fiber is cleaved and can be spliced with another fiber, depending on the experience. In figure 2, the energy of the laser light at the output of the fiber is compared to the energy emitted by the laser for two repetition rates (10 Hz and 20 Hz) as functions of the pulse duration.

The samples used are C/epoxy plates T300/914 and their surface are painted in white to increase the signal-to-noise ratio. The arrangement of the fibers in the sample is described in figure 3. In the first set of experiments, the output fiber is approached near the surface of the sample, this is a « classical » optical fiber guided ultrasound laser experiment. In the second set of experiments, the fiber is embedded in the material after the process, i.e. glued inside a hole. In the third set of experiments, the fiber is embedded in the material during the process as shown in figure 3. In each case, the delivery fiber is spliced to the input fiber. The fourth set of experiments is identical to the first one, but the sample is then a colored epoxy resin plate.

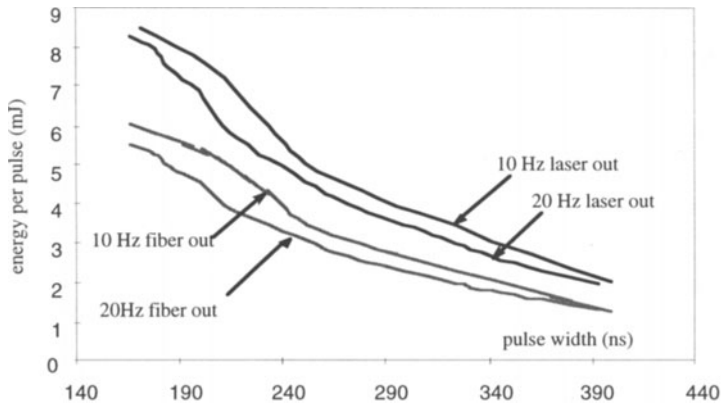


Figure 2. Energy per pulse as a function of the pulse width for two repetition rates.

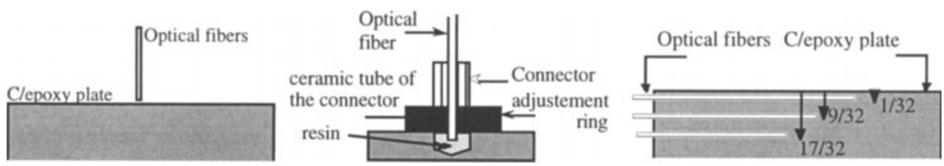


Figure 3. Arrangement of fibers in the sample. Left : Surface generation. Middle : fibers embedded after the process. Right : fibers embedded during the process.

## RESULTS

### Fiber Outside of the Composite and Close to the Surface

In this case, the optical fiber is placed close to the surface of the composite plate, the detection is performed on the opposite side, at the epicenter. We can notice in figure 4 that the arrival times of both longitudinal and shear waves will agree with piezoelectric measurements. The time distribution corresponds very precisely to the one predicted by the model [2]. The damage threshold of the composite is experimentally found to be equal to 4 mJ for a pulse of 230 ns and a spot radius of 0.85 mm.

### Fiber Embedded After the Process

In this experiment, we try to know how the detected signal is modified with respect to the previous results when the source energy is deposited inside the material. The particular arrangement of the fiber inside the sample is described in figure 3. The energy in the material cannot be measured directly and we can only give an approximated value taking into account the losses in the splice (0.07 dB) and the values measured previously with fibers alone.

We clearly see in figure 5 that the shapes of the generated waves are quite different from the ones obtained in the first experiment. A first explanation can be proposed : the heated zone is closer to the detection point than in the first case (dimension of the hole), the longitudinal wave arrives more quickly so that the temporal width of the precursor is more important [2]. We also notice that the thermoelastic regime is kept because the detected signal is proportional to the input energy. The damage threshold is about 4 mJ. When the detection is scanned across the epicenter, the experiments have shown that the amplitude of the signal decreases very quickly, but the arrival times are kept identical. This result is representative of a large source, probably induced by light scattering in the glue.

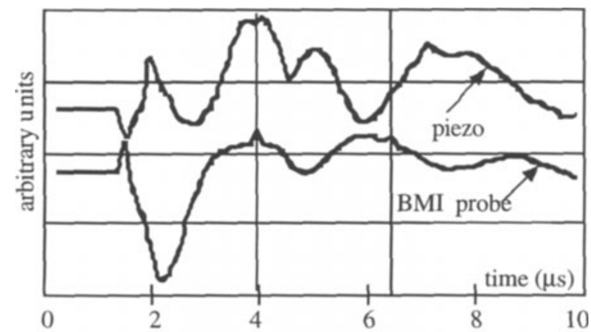


Figure 4. Fiber close to the surface, comparison between the optical probe and piezo transducer detections at the epicenter of the opposite face.

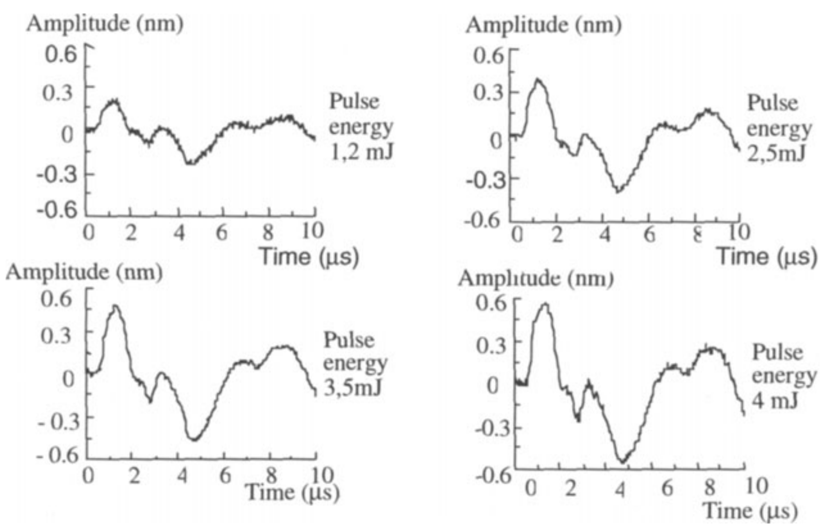


Figure 5. Ultrasound generation by a fiber glued in a hole. Rear face displacements at the epicenter. Influence of the pulse energy (2000 shots, f=10 Hz).

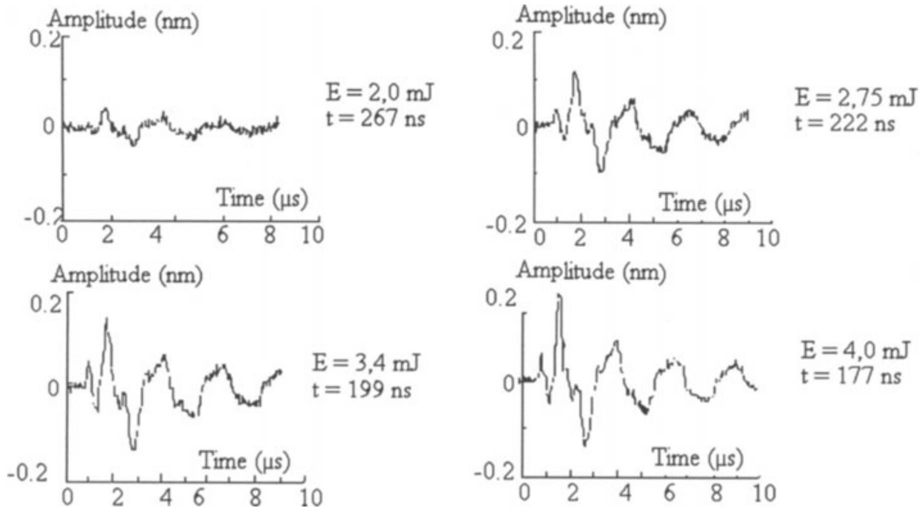


Figure 6. Ultrasound generation with fibers embedded during the process. Variation of the ultrasounds amplitudes with the pulse energy. Splice losses are not taken into account in the values of E. Amplitudes are averaged over 2000 shots, the repetition frequency is f = 20 Hz.

Fiber Embedded During the Process

For these experiments the optical fibers were embedded inside the composite during the process, located between two parallel plies as shown in figure 2. Three fibers were embedded at different locations inside the composite. The results presented here are given for the fiber located in the middle of the plate. As for the case of the glued fiber, the knowledge of the amount of energy at the fiber output is not precise but, the energy delivered can be supposed comparable to that of the previous configuration. Nevertheless, as seen in figure 6, the detected signal is roughly a third of the one of figure 5 in the same conditions.

A post-test destructive examination of the sample is presented in figures 7 and 8 and allows to observe the degradation of both fiber and resin. We can also notice that a cone of resin exists at the tip of the fiber. We can explain these damages by considering that the energy is mainly absorbed by the carbon fibers since the resin is transparent at the wavelength of the laser. The heat created in the carbon fibers diffuses through the resin, heats it and then can damage both the fiber and the resin.

Fiber Outside a Colored Epoxy Plate

We saw in the last experiment that the laser-ultrasound conversion is poor, and the damage threshold of the composite is rather low. A possible solution could be to use an intermediate medium between the fiber and the material. This medium must have a high thermal expansion coefficient, a large optical absorption coefficient at $\lambda$=1.06 µm and a good acoustical coupling factor with the medium in which the ultrasounds propagate. A good solution could be to color the resin used in the composite with an adapted dye. The set-up used to test this solution is the same as the one of the first experiments, i.e. that the optical fiber is located close to the surface of the sample, perpendicular to its surface. In figure 9 we observe that the detected signal is much higher than the one obtained in the first experiments. Finally, the arrival times are of the same order as in pure resin, so that it seems that the presence of dye doesn't modify the mechanical properties of the resin, nevertheless, this new material is still not well characterized and specially the control of the optical absorption by varying the dye concentration is not totally achieved.

## DISCUSSION

The first conclusion of all these observations is that the generation of ultrasounds through optical fibers embedded in a composite is not improved with respect to what is observed in the case of the surface generation (figure 10). It is often mentioned that the former excitation is normally more efficient than the latter since it implies constrained boundary conditions which normally increases the amplitude of the generated ultrasounds. A possible explanation of this surprising result is that absorption of the pulsed light is mainly achieved by the carbon fibers in which very small acoustic conversion is obtained because the thermal expansion of this material is very low. The low detected signal could also be explained by the

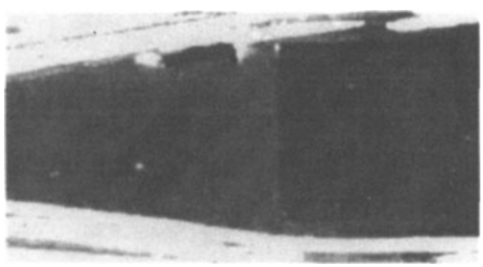

Figure 7. Post-test destructive examination: undamaged optical fiber.

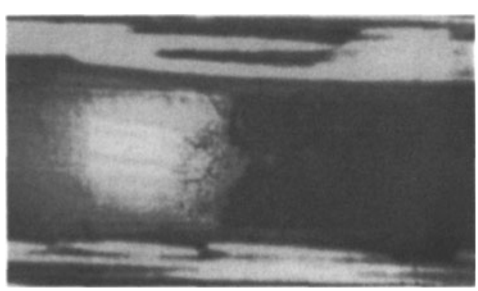

Figure 8. Post-test destructive examination: damaged resin and fiber.

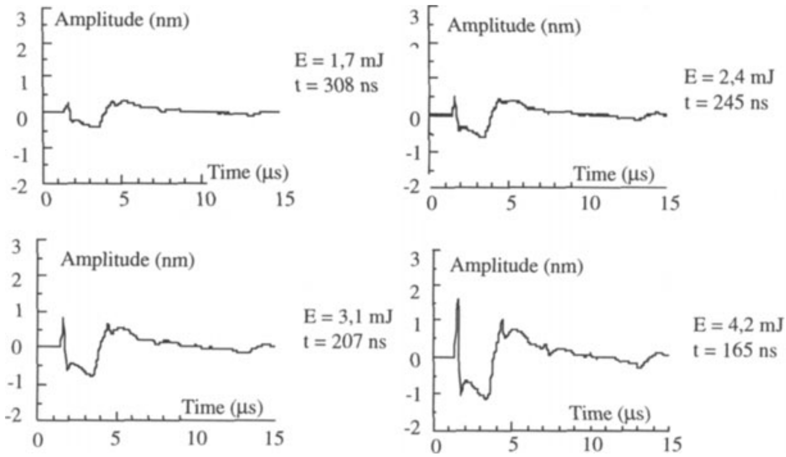


Figure 9. Excitation of a colored epoxy plate via an optical fiber outside of the sample. Rear face displacements - Influence of pulse energy. Distance between optical fiber tip and sample surface : D = 6 mm, spot size =1.14 mm, f = 20 Hz, amplitudes averaged with 400 shots.

fact that the generation is performed in a different way. In the previous experiment, the laser beam from the optical fiber tip was directed perpendicular to the plies but in this experiment, the laser beam from the optical fiber is directed parallel to the plies. The mechanical energy can be guided by the fibers, explaining the low level of the detected signal on the opposite face at the epicenter. Measurement of the displacement are to be done on the lateral side of the plate to validate this assumption.

The second conclusion is that this kind of composite is very fragile and has a very low threshold damage when embedded optical fibers are used to directly illuminate the material. The reason of this fragility should be related to the localization of the optical absorption in a very small volume, the one of the carbon fibers. Hence, it seems that the generated waves in a carbon composite before any modification of the epoxy are too weak to be used in NDE. But this method could be employed for other materials : as shown by the experiments with the colored epoxy, it is possible to use an intermediate material which will absorb the laser energy and then will generate ultrasounds of larger amplitudes owing to the thermoelastic mechanism (see experiments with the fiber glued in the hole) without any damage. Of course, it is not necessary to prepare the whole composite plate with a colored resin but the selected resin can be placed at the end of the optical fiber during the process in order to progressively absorb the laser energy before it reaches the carbon fiber. In the experiments described in this paper, in order to not modify the mechanical properties of the composite plate, small multimode optical fibers were used. Another way to improve the ultrasound generation is to use higher diameter optical fibers which could be embedded in different composite structures or in a non mechanically solicited part of the composite. The large signals which could be generated with such a fiber could allow easier detection of ultrasounds, even after propagation on large distances.

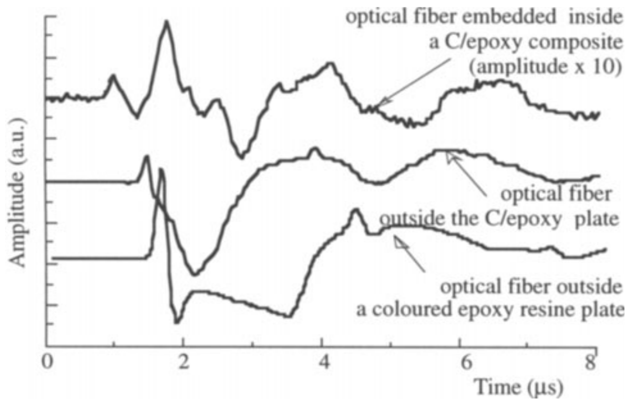


Figure 10. Optical probe signal corresponding to various configurations

## CONCLUSION

We shown that it is possible to generate ultrasounds by laser pulses through optical fibers inside a composite plate, but that this direct method is not convenient for NDE applications because of the low damage threshold of the composite and its poor opto-acoustical conversion. A promising way of research is the implementation of an intermediate material between the fiber tip and the composite fiber which would enhance the laser conversion and decrease the threshold damage. For this new research we propose a doped dye resin semi transparent at the Nd : YAG wavelength for which the amplitude of the generated waves could be ten times higher than the one obtained in the case of the fiber embedded directly in the composite. Our future work will be based on the development of these ideas, in complement with the research of optical fibers embedded and used as sensors and the special generation of Lamb waves which are well adapted to NDE applications in plates.

## ACKNOWLEDGMENTS

We thank B. Bloch for the preparation of the colored resin and J. P. Favre and A. Mavel for the post-test examination.

## REFERENCES

1. C. B Scruby and L. E. Drain, Laser Ultrasonics : Techniques and Applications (Adam Hilger, Bristol, 1990).
2. R. Coulette, E. Laffond, F. Lepoutre, D. Balageas, M.-H Nadal and C. Gondard, to be published in this issue of Review of QNDE.